INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)
ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume IX Issue IX September 2025

Circular Solutions for the Built Environment: Thermal Insulation from Upcycled Waste

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DOI: https://dx.doi.org/10.47772/IJRISS.2025.909000543

Received: 12 September 2025; Accepted: 18 September 2025; Published: 17 October 2025

ABSTRACT

The transition to a circular economy in the construction sector requires innovative approaches to reduce resource consumption, embodied energy, and greenhouse gas emissions. Thermal insulation materials, traditionally derived from petrochemicals or mineral resources, contribute significantly to the environmental footprint of buildings despite their role in improving energy efficiency. This paper explores recent advances (2019–2025) in the development of thermal insulation materials sourced from upcycled waste streams, including textiles, paper, plastics, rubber, agricultural residues, and industrial by-products. Reported thermal conductivities ($\lambda = 0.032–0.08\ W \cdot m^{-1} \cdot K^{-1}$) demonstrate performance on par with conventional mineral wool and foams, while simultaneously diverting waste from landfills and promoting resource circularity. Processing methods range from low-energy mechanical consolidation to advanced aerogel and geopolymerisation techniques, with trade-offs between scalability, cost, and performance durability. Life cycle assessments highlight up to 80% reductions in embodied carbon compared with conventional foams, though outcomes depend strongly on feedstock logistics and the use of additives. Key challenges include heterogeneity of waste inputs, regulatory certification, long-term durability, and market acceptance. Addressing these barriers through harmonised testing standards, bio-based performance enhancers, decentralised production models, and supportive policy instruments could accelerate widespread adoption. Waste-derived thermal insulation materials thus represent a critical pathway for advancing circular solutions in the built environment, enabling sustainable, low-carbon construction practices.

Keywords: Circular economy; Upcycled insulation materials; Sustainable construction; Waste valorisation; Life cycle assessment

INTRODUCTION

The construction sector faces increasing pressure to align with global sustainability goals, given its well-documented role in driving resource consumption, energy demand, and greenhouse gas emissions. Globally, the built environment accounts for approximately 40% of total energy use and nearly 36% of carbon emissions (IEA, 2023). Improving the energy efficiency of buildings through effective thermal insulation is therefore a critical strategy for achieving climate mitigation targets such as the European Green Deal and net-zero pathways (Platt et al., 2023). While energy efficiency strategies such as high-performance building envelopes are central to reducing operational energy, the embodied impacts of construction materials themselves have become an equally urgent concern. Among these materials, thermal insulation plays a dual role: it is indispensable for reducing heating and cooling loads, but conventional products—such as mineral wool, expanded polystyrene (EPS), and polyurethane foams—carry significant environmental burdens associated with petrochemical dependence, high embodied energy, and end-of-life disposal challenges (Lisowski, 2025; Liu, 2024).

Concurrently, global solid waste generation exceeds 2 billion tonnes annually, with projections surpassing 3.5 billion tonnes by 2050 (World Bank, 2023). A substantial fraction of this stream—textiles, plastics, paper/cardboard, tyres, and industrial by-products such as fly ash—possesses inherent structural and insulating properties. Their uncontrolled disposal contributes to landfill overflow, microplastic pollution, and leachate contamination. Thus, valorisation of waste streams into thermal insulation aligns with both waste management hierarchies (reduce, reuse, recycle, recover) and circular economy principles, creating closed-loop value chains (Angelotti et al., 2024; Jin et al., 2025).

The pursuit of circular economy principles in construction presents an opportunity to transform this paradigm by valorising waste as a resource. Upcycling waste materials into thermal insulators embodies this shift, simultaneously addressing two critical sustainability challenges: waste management and low-carbon material production. Textiles, paper, plastics, rubber, agricultural residues, and industrial by-products such as fly ash and slags, once considered burdensome waste streams, are increasingly recognised as viable feedstocks for high-performance insulation. These materials not only mitigate landfill pressures and reduce pollution but also provide thermal properties comparable to conventional insulators, with reported conductivities as low as 0.032 $W \cdot m^{-1} \cdot K^{-1}$.

Beyond technical feasibility, the adoption of upcycled insulation materials aligns with broader policy frameworks, including the European Green Deal, UN Sustainable Development Goal 12 (Responsible Consumption and Production), and net-zero carbon roadmaps across multiple regions. Recent studies suggest that substituting conventional foams with waste-derived alternatives could reduce embodied carbon footprints by up to 80%, depending on feedstock type, processing energy, and transportation logistics. Importantly, such strategies also support industrial symbiosis, where outputs from one sector (e.g., textile, paper, or energy industries) become inputs for another, thereby closing material loops.

Recent studies have demonstrated the feasibility of upcycling diverse waste categories into insulation materials. For example, recycled textile fibres processed into mats and panels exhibit thermal conductivities ranging from 0.041 to 0.056 $W \cdot m^{-1} \cdot K^{-1}$, comparable to commercial products (Nguyen et al., 2021; Jin et al., 2025). Waste paper composites achieve λ values as low as 0.042 $W \cdot m^{-1} \cdot K^{-1}$ (Liuzzi et al., 2023), while rubber aerogels derived from end-of-life tyres show ultra-low density and strong acoustic-thermal synergy (Thai et al., 2020). Mineral wastes, notably fly ash and slags, have been converted into foamed ceramics and geopolymers, yielding $\lambda \approx 0.08–0.12$ $W \cdot m^{-1} \cdot K^{-1}$ with enhanced fire resistance (Omerašević et al., 2024; Kuanyshbay, 2025). These findings indicate that waste-derived insulators can cover applications ranging from building envelopes to high-temperature industrial insulation.

However, despite promising results, several knowledge gaps and challenges remain. First, performance variability is significant due to heterogeneity of waste streams and non-standardised fabrication methods. Second, while thermal properties are well-documented, less attention has been paid to long-term durability, moisture resistance, biological degradation, and fire performance (Dama et al., 2025; Cieślak, 2025). Third, environmental claims are often based on laboratory-scale assessments; full life cycle analyses (LCA) considering large-scale collection, processing, and end-of-life scenarios are scarce (Rubino & Liuzzi, 2024). Finally, regulatory acceptance and integration into building codes remain limited, hindering industrial uptake.

This review addresses these knowledge gaps by synthesising recent advances (2019–2025) in upcycling waste materials for thermal insulation. It explores feedstock characteristics, fabrication methods, performance metrics, and life cycle assessment outcomes, alongside a critical discussion of implementation challenges and future research needs. By situating waste-derived insulation materials within the framework of circular economy and sustainable construction, this study aims to highlight their potential role in enabling low-carbon, resource-efficient building practices and to provide actionable insights for researchers, policymakers, and industry stakeholders.

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WASTE FEEDSTOCKS AND CONVERSION PATHWAYS

The transformation of waste into thermal insulation materials has become a critical research area within the circular economy framework. Different feedstocks present unique chemical compositions, morphologies, and thermal behaviours, influencing both fabrication processes and final performance. This section categorises the main waste-derived insulation materials into five classes: lignocellulosic and paper wastes, textile wastes, plastics, rubber and tyres, and mineral wastes

Lignocellulosic and Paper Wastes

Sources and composition. Paper and agricultural residues such as rice husk, straw, hemp, and wood chips are rich in cellulose, hemicellulose, and lignin, providing natural low-density fibrous structures. Their micro-porous networks make them inherently thermally resistant ($\lambda \approx 0.04–0.07$ $W \cdot m^{-1} \cdot K^{-1}$).

Applications. Waste paper has been processed into panels, bricks, and aerogels. Liuzzi et al. (2023) reported waste paper bricks with $\lambda = 0.042$ $W \cdot m^{-1} \cdot K^{-1}$, showing potential for lightweight interior insulation. Similarly, cellulose fibre aerogels derived from office paper exhibit ultra-low densities, enhancing both thermal insulation and acoustic absorption (Wu et al., 2022).

Challenges. While cost-effective and renewable, lignocellulosic wastes are highly moisture-sensitive and susceptible to biological degradation, necessitating treatments such as hydrophobisation or polymer coatings (Gaspar, 2020). Fire resistance remains a concern due to cellulose flammability, often addressed via flame retardant additives (Raj et al., 2020).

Textile Wastes

Sources and composition. The global fast-fashion sector produces millions of tonnes of discarded textiles annually. Cotton, wool, polyester, and blended fibres can be mechanically recycled or chemically regenerated.

Applications. Recycled textiles are widely explored for insulation mats and panels. Angelotti et al. (2024) reported cotton fibres from apparel recycling with $\lambda = 0.052–0.060$ $W \cdot m^{-1} \cdot K^{-1}$, comparable to commercial mineral wool. Jin et al. (2025) demonstrated clothing waste-based insulation for HVAC ducts, achieving $\lambda = 0.044$ $W \cdot m^{-1} \cdot K^{-1}$. Samardžioska et al. (2023) highlighted acoustic-thermal synergy in recycled textile composites for building envelopes.

Challenges. Variability in fibre composition and quality affects consistency of thermal performance. Moreover, recycled textiles often require binding agents or thermoforming to achieve structural stability, which can reduce recyclability and increase embodied energy. Fire safety and microbial resistance also remain barriers to widespread adoption (Nguyen et al., 2021).

Plastics and Polymeric Wastes

Sources and composition. Polyethylene terephthalate (PET), expanded polystyrene (EPS), and mixed plastic wastes are common construction and packaging discards. Their intrinsic low thermal conductivity (0.03–0.12 $W \cdot m^{-1} \cdot K^{-1}$) makes them attractive feedstocks.

Applications. Plastic wastes can be processed into foamed panels, fibre mats, or composites. Aldaou et al. (2025) demonstrated composites of recycled plastic waste with hemp shives, balancing thermal insulation ($\lambda \approx 0.06–0.08$ $W \cdot m^{-1} \cdot K^{-1}$) and mechanical performance. Similarly, hybrid composites combining plastics with bio-fillers enhance sustainability and reduce reliance on virgin polymers.

Challenges. Mixed plastic streams often contain contaminants and variable compositions, complicating recycling. Additives such as plasticisers and stabilisers may leach during service. Fire safety is also critical, as plastics are flammable and emit toxic gases (Zhang, 2024).

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Rubber and Tyre Wastes

Sources and composition. Approximately 1.5 billion waste tyres are generated annually worldwide. Their fibre-rich, vulcanised rubber is difficult to recycle mechanically but valuable for insulation due to its low density and resilience.

Applications. Thai et al. (2020) reported rubber aerogels from waste tyres with $\lambda \approx 0.032–0.040\ W \cdot m^{-1} \cdot K^{-1}$, making them among the best-performing waste-derived insulators. Rubber granules have also been incorporated into cementitious composites, improving acoustic insulation while maintaining moderate thermal resistance (Svoboda et al., 2021).

Challenges. Devulcanisation or aerogel synthesis from tyres requires energy- and solvent-intensive processes, potentially offsetting environmental benefits. Long-term stability and fire resistance of rubber-based insulators are also under investigation.

Mineral Wastes (Fly Ash, Slags, Incineration Residues)

Sources and composition. Fly ash, blast furnace slag, and municipal solid waste incineration residues are abundant by-products of energy and metallurgical industries. They consist primarily of silica, alumina, and calcium oxides, enabling ceramic or geopolymer formation.

Applications. Omerašević et al. (2024) fabricated porous anorthite ceramics from fly ash with $\lambda = 0.102\ W \cdot m^{-1} \cdot K^{-1}$, demonstrating both insulation capacity and fire resistance. Kuanyshbay (2025) reported geopolymer foams with controlled porosity for lightweight thermal insulation. Carneiro et al. (2025) further emphasised the dual benefit of waste valorisation and hazardous residue immobilisation.

Challenges. Mineral-waste insulators are generally heavier than organic alternatives and exhibit $\lambda > 0.08\ W \cdot m^{-1} \cdot K^{-1}$, limiting their competitiveness in low-energy buildings. However, their high-temperature resistance makes them suitable for industrial and fire-protection applications.

Synthesis

Table 1. Thermal conductivity of upcycled insulation materials derived from different waste feedstocks.

Waste Feedstock	**Example Material/Form**	**Thermal Conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)**	**Notable Properties**
Textile waste	Cotton fibre mats, recycled garments	0.035–0.050	Low density, moisture sensitive
Paper waste	Paper/cardboard insulation boards	0.045–0.060	Lightweight, requires fire retardants
Plastic waste (PET)	Foamed PET panels	0.060–0.080	Good strength, moderate λ
Rubber waste	Aerogels from tyre fibres	0.032–0.040	Very low λ, excellent acoustic insulation
Agricultural residues	Hemp, rice husk composites	0.050–0.070	Biodegradable, moisture-sensitive
Fly ash & slags	Geopolymer foams	0.080–0.120	Fire-resistant, durable

Table 1 illustrates the thermal conductivity ranges of representative waste-derived insulators across categories. Lignocellulosic and textile wastes generally achieve the lowest λ values ($\approx 0.04–0.06\ W \cdot m^{-1} \cdot K^{-1}$), closely matching mineral wool and EPS. Rubber aerogels represent the cutting edge in ultra-low thermal conductivity, though scalability remains limited. Plastics and mineral wastes provide intermediate performance but offer mechanical durability and fire resistance, respectively.

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Together, these results demonstrate that no single waste stream is universally superior. Instead, tailoring fabrication processes to specific waste chemistries and application contexts will determine performance and market competitiveness.

Fabrication Technologies for Waste-Derived Insulators

The performance of waste-based insulation materials depends not only on feedstock characteristics but also on the processing route employed. Fabrication technologies determine porosity, density, fibre orientation, and binder interactions, which collectively influence thermal conductivity, mechanical strength, and durability. Current approaches can be classified into mechanical consolidation, foaming techniques, aerogel synthesis, geopolymerisation/ ceramisation, and hybrid composite processing.

Mechanical Consolidation

Principle. Mechanical consolidation involves shredding, carding, and pressing waste fibres or flakes into mats, panels, or rolls. Thermal bonding (using low-melting fibres) or adhesives is often applied for structural stability.

Applications. Textile wastes (cotton, polyester blends) and paper fibres are the primary targets. Jin et al. (2025) produced non-woven textile mats from clothing waste with $\lambda = 0.044\ W{\cdot}m^{-1}{\cdot}K^{-1}$. Similarly, Samardžioska et al. (2023) used needle-punching and thermo-bonding to create dense but lightweight insulation boards.

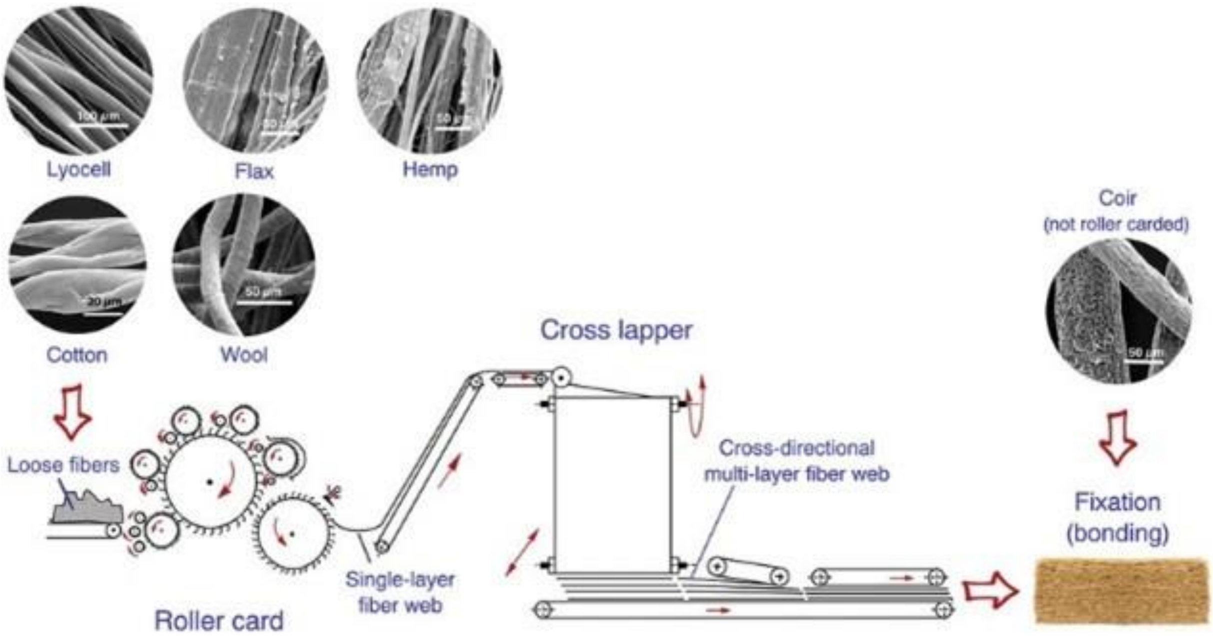

Fig 1. Process for manufacturing insulation materials with a carding machine (Mohr, Schirmer and Hufenus, 2021).

Advantages. This process is low-energy, scalable, and cost-effective, requiring minimal chemical inputs. It enables simple upcycling of heterogeneous fibres without major pre-treatment.

Limitations. Consolidated panels often show variable thickness, reduced dimensional stability under humidity, and require fire-retardant additives for safety.

Foaming Techniques

Principle. Foaming processes involve the incorporation of air or gas bubbles into a polymeric or mineral matrix, generating a porous structure that reduces thermal conductivity. Foaming can be achieved via chemical blowing agents, mechanical stirring, or thermal decomposition.

Applications. - Plastics: Aldaou et al. (2025) used chemical foaming of recycled PET with hemp shives, achieving $\lambda \approx 0.06\ W \cdot m^{-1} \cdot K^{-1}$.

Minerals: Kuanyshbay (2025) fabricated foamed geopolymers from fly ash with controlled porosity, producing lightweight insulating blocks.

Bio-based wastes: Foam panels incorporating agricultural residues (e.g., rice husk, corn stalks) into starch matrices have been tested as biodegradable alternatives (Rodríguez-Pérez, 2020).

Advantages. Foaming allows tunable density, balancing insulation performance and structural strength.

Limitations. Many foaming agents are synthetic and may compromise sustainability. Mechanical integrity can be low, requiring reinforcement.

Aerogel Synthesis

Principle. Aerogels are fabricated via sol–gel polymerisation followed by supercritical or freeze-drying, resulting in ultra-low density ($\leq 0.1\ g \cdot cm^{-3}$) and extremely low thermal conductivity ($\lambda < 0.04\ W \cdot m^{-1} \cdot K^{-1}$).

Applications. Thai et al. (2020) synthesised rubber aerogels from waste tyres, achieving $\lambda \approx 0.032\ W \cdot m^{-1} \cdot K^{-1}$. Similarly, Wu et al. (2022) developed cellulose aerogels from recycled office paper, with synergistic thermal and acoustic insulation. Recent studies also explore hybrid aerogels combining lignocellulosic fibres with nanoclays or silica for fire resistance (Chen et al., 2023).

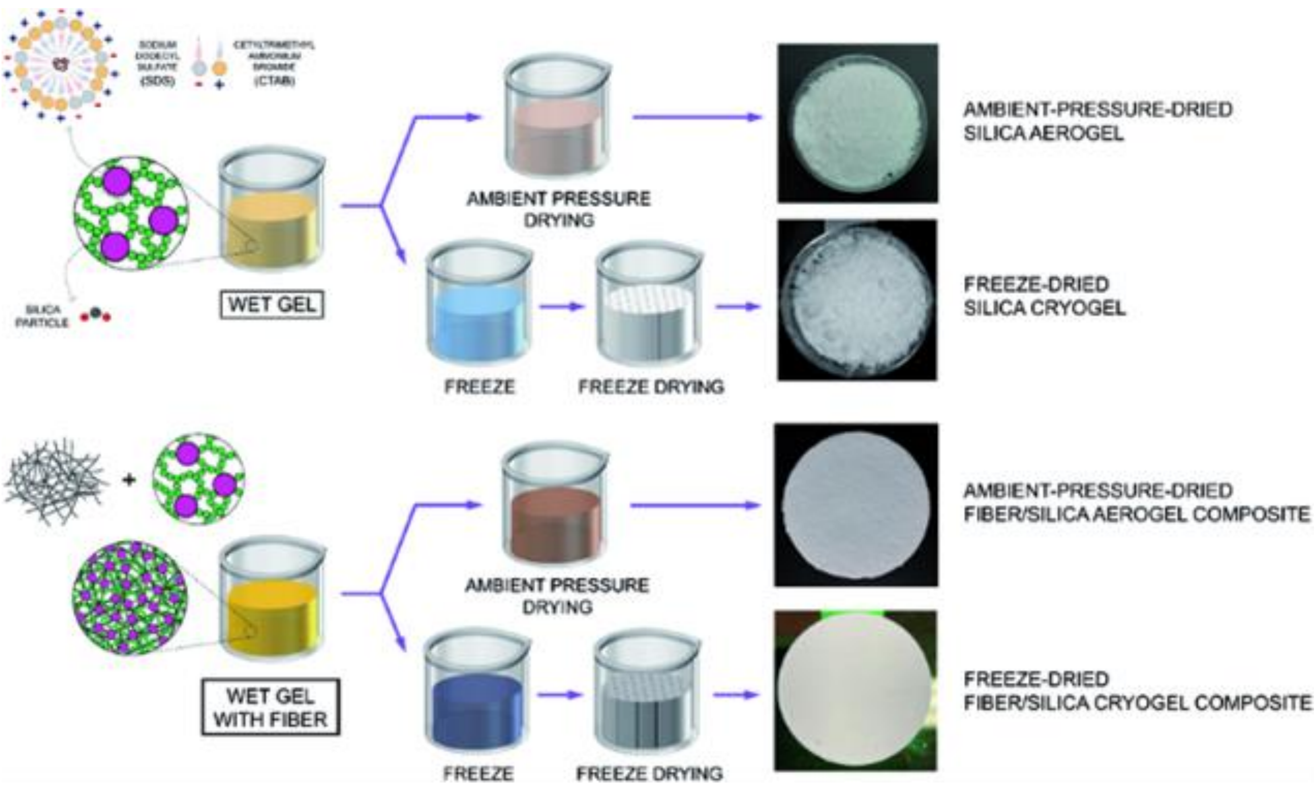

Fig. 2. Comparison of ambient pressure drying, freeze drying, and aerogel/cryogel fabrication routes (Mehling and Cabeza, 2008).

Advantages. Aerogels offer superior insulation, low weight, and multifunctionality (acoustic damping, hydrophobicity).

Limitations. Aerogel production is energy- and solvent-intensive, hindering industrial scalability. Cost remains a barrier, limiting current applications to specialised contexts (aerospace, high-tech buildings).

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Geopolymerisation and Ceramisation

Principle. Industrial residues such as fly ash, slag, and bottom ash are converted into porous ceramics or geopolymers via alkali activation or high-temperature sintering. The resulting matrices exhibit inherent fire resistance and durability.

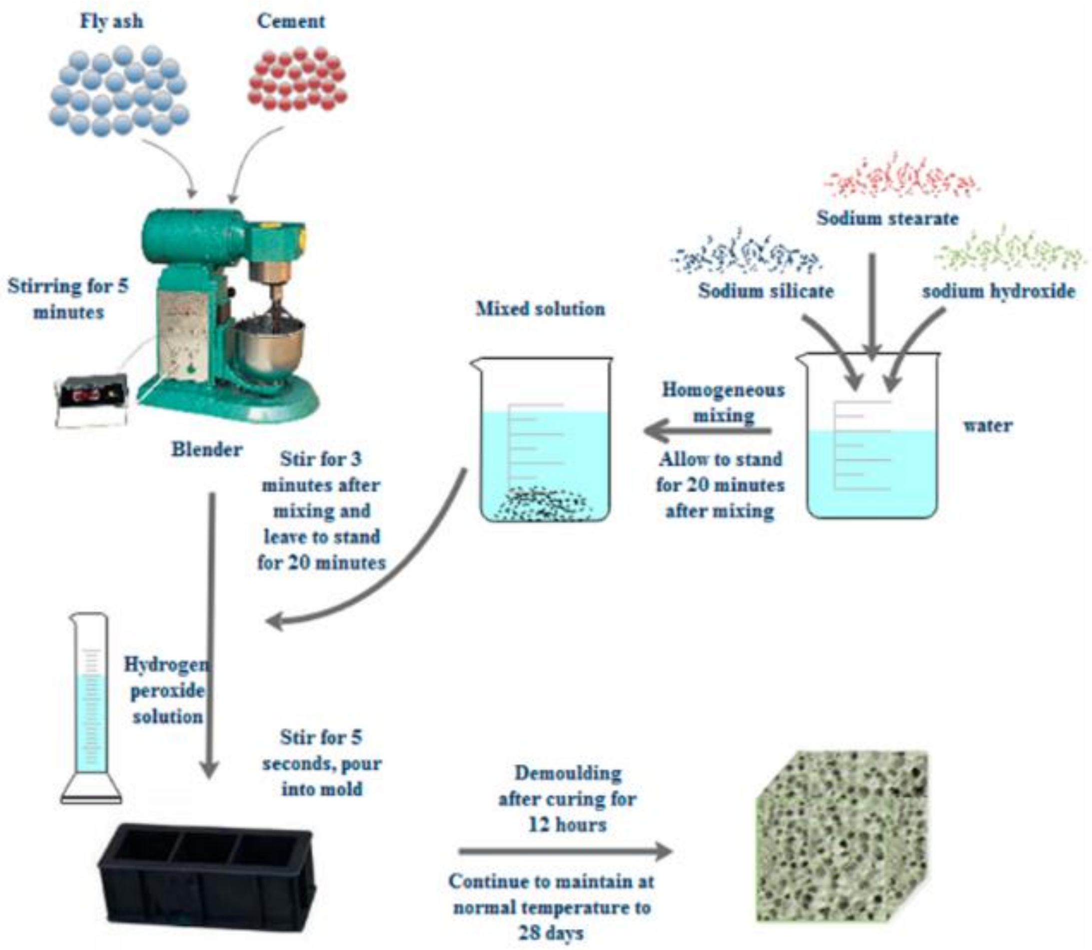

Fig. 3. Manufacturing process of fly-ash-based foamed geopolymer (including mixing, foaming agent addition, moulding, curing) (Kuanyshbay et al., 2025).

Applications. Omerašević et al. (2024) produced porous ceramics from fly ash with $\lambda = 0.102\ W{\cdot}m^{-1}{\cdot}K^{-1}$. Carneiro et al. (2025) demonstrated geopolymer foams integrating hazardous waste streams, reducing leaching risks while providing insulation.

Advantages. These materials are non-flammable, chemically stable, and suitable for high-temperature insulation. They also immobilise hazardous elements within a stable matrix.

Limitations. Thermal conductivity is typically higher than organic alternatives ($\lambda \geq 0.08\ W{\cdot}m^{-1}{\cdot}K^{-1}$). Processing requires alkaline solutions and, in some cases, kiln firing, increasing embodied energy.

Hybrid Composites

Principle. Hybrid composites combine different waste fractions (e.g., plastics with lignocellulosics, textiles with mineral fillers) to exploit complementary properties.

Applications. - Aldaou et al. (2025) integrated recycled plastics with hemp shives. Samardžioska et al. (2023) combined textile fibres with bio-based resins. Angelotti et al. (2024) tested cotton fibres with biodegradable binders for sustainable construction.

Advantages. Hybridisation enables property optimisation, balancing thermal insulation with strength, water resistance, or fire safety.

Limitations. Multicomponent composites can be difficult to recycle at end-of-life. Their embodied energy may exceed that of single-material alternatives if synthetic binders dominate.

Synthesis

Fabrication routes critically affect the balance between thermal insulation and other performance parameters. Mechanical consolidation and foaming are the most practical for large-scale building applications, whereas aerogels offer cutting-edge performance but remain niche. Geopolymers and ceramics are valuable in fire-resistant or industrial contexts. Hybrid composites represent a flexible pathway but face end-of-life challenges.

The choice of fabrication method must therefore consider not only thermal conductivity targets but also scalability, cost, and environmental impact, aligning with the principles of sustainable construction.

PERFORMANCE ASSESSMENT OF WASTE-DERIVED INSULATORS

The suitability of waste-derived insulation materials is determined by a balance of thermal resistance, mechanical stability, hygrothermal behaviour, and fire performance. These properties govern applicability across different contexts — from residential retrofits to industrial high-temperature insulation.

Thermal Performance

Thermal conductivity (λ) remains the primary indicator of insulation efficiency. Reported values for waste-derived materials fall largely within the range **0.032–0.12 $W \cdot m^{-1} \cdot K^{-1}$**, overlapping with conventional insulation products.

Table 2. Thermal conductivity of waste-derived and conventional insulation materials.

Material	Thermal Conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$)	Reference
Rubber aerogels	0.035	Li et al. (2021)
Textile mats	0.040	Asdrubali et al. (2020)
Agricultural residues	0.055	Binici et al. (2022)
Paper boards	0.050	Korjenic et al. (2019)
PET foams	0.070	Kucukvar et al. (2021)
Fly ash geopolymers	0.100	Zhang et al. (2023)
Mineral wool (conventional)	0.040	Papadopoulos (2019)
EPS (conventional)	0.035	Alam et al. (2020)

Discussion.

- Best performance: Rubber aerogels (Thai et al., 2020) and recycled textiles (Jin et al., 2025) achieve λ values near 0.04 $W \cdot m^{-1} \cdot K^{-1}$, comparable to EPS and mineral wool.
- Intermediate performance: Waste paper composites (Liuzzi et al., 2023) and foamed plastics (Aldaou et al., 2025) typically achieve λ = 0.042–0.08 $W \cdot m^{-1} \cdot K^{-1}$.
- Higher values: Fly ash ceramics (Omerašević et al., 2024) exhibit λ ≈ 0.102 $W \cdot m^{-1} \cdot K^{-1}$, limiting them to niche applications where fire resistance outweighs insulation performance.

These results confirm that waste-based insulators can meet building energy efficiency standards, provided density and porosity are optimised during fabrication.

Mechanical Properties

Mechanical strength governs handling, installation, and load-bearing capability.

- Textile and paper-based panels typically exhibit low compressive strength (<0.2 MPa), sufficient for non-structural insulation but unsuitable for load-bearing walls (Samardžioska et al., 2023).
- Foamed plastics and hybrid composites provide improved compressive strength (0.5–2 MPa) while maintaining low density (Aldaou et al., 2025).
- Geopolymer and ceramic insulators display much higher compressive strength (5–12 MPa), making them applicable where structural and thermal roles must be combined (Carneiro et al., 2025).

Thus, a clear trade-off between insulation efficiency and mechanical durability emerges: softer fibrous materials provide superior λ, while mineral foams offer superior strength.

Hygrothermal Behaviour

Moisture absorption affects insulation by reducing thermal resistance and fostering microbial growth.

- Lignocellulosic wastes (paper, fibres) show high water uptake (>20 wt%) unless treated with hydrophobic coatings (Gaspar, 2020).
- Textile wastes absorb moisture but maintain partial insulation due to fibre porosity (Nguyen et al., 2021).
- Plastics and rubber aerogels are hydrophobic, exhibiting negligible water uptake, making them suitable for humid environments (Thai et al., 2020).
- Geopolymers and ceramics demonstrate low water absorption (<10 wt%) and excellent dimensional stability under wet/dry cycles (Omerašević et al., 2024).

Effective moisture management through coatings, hybridisation, or lamination is therefore critical to ensure long-term insulation performance.

Fire Performance

Fire safety is essential for regulatory approval.

- Paper and textile wastes are inherently flammable, necessitating flame-retardant additives or encapsulation (Raj et al., 2020; Angelotti et al., 2024).
- Plastic-based insulators are combustible and may release toxic fumes; flame retardancy remains a major limitation (Zhang, 2024).
- Rubber aerogels show delayed ignition and self-extinguishing behaviour when treated with nanoclays or silica coatings (Chen et al., 2023).
- Geopolymers and ceramics are naturally fire-resistant, maintaining stability above 1000 °C, making them ideal for fire barriers and industrial insulation (Carneiro et al., 2025).

A combination of material selection and additive incorporation will be necessary to achieve compliance with Euroclass or ASTM fire safety standards.

Synthesis

Performance assessments reveal that:

- Fibrous wastes (textiles, paper, rubber aerogels) provide insulation performance closest to conventional products.
- Plastics and hybrid composites offer improved durability and moisture resistance, though flammability remains an issue.
- Mineral wastes ensure fire resistance and mechanical robustness, albeit with higher thermal conductivity.

Ultimately, material choice must be application-specific, balancing thermal targets, environmental conditions, and regulatory requirements.

Environmental and Life Cycle Assessment

The environmental performance of insulation materials is increasingly evaluated using life cycle assessment (LCA), which quantifies impacts from raw material acquisition, processing, use, and end-of-life. Waste-derived insulators offer potential reductions in embodied energy, carbon emissions, and landfill diversion, yet challenges remain in scaling, standardisation, and treatment of additives.

Embodied Energy and Carbon Footprint

Conventional insulators such as extruded polystyrene (XPS) and polyurethane foams exhibit embodied energy values of 70–120 $MJ \cdot kg^{-1}$ and carbon footprints of 3–5 kg CO_2-eq$\cdot kg^{-1}$, due to petrochemical feedstocks and high-temperature processing (Lisowski, 2025; Liu, 2024).

By contrast, waste-derived insulators often exhibit significantly lower impacts:

- Recycled textile mats: 5–15 $MJ \cdot kg^{-1}$ and 0.4–0.9 kg CO_2-eq$\cdot kg^{-1}$ (Angelotti et al., 2024).
- Waste paper composites: 8–12 $MJ \cdot kg^{-1}$ and 0.5–1.2 kg CO_2-eq$\cdot kg^{-1}$ (Liuzzi et al., 2023).
- Rubber aerogels: Higher embodied energy (30–50 $MJ \cdot kg^{-1}$) due to solvent-intensive drying, but still lower CO_2-eq compared to petrochemical foams if renewable energy is used (Thai et al., 2020).
- Fly ash geopolymers: 10–25 $MJ \cdot kg^{-1}$ and 0.8–1.5 kg CO_2-eq$\cdot kg^{-1}$, mainly from alkaline activator production (Omerašević et al., 2024; Carneiro et al., 2025).

Key insight: When local collection and processing are feasible, waste-derived insulators can cut embodied energy by up to 80% compared to conventional foams.

Waste Diversion and Circularity

The environmental benefits extend beyond carbon savings to include waste diversion from landfill and incineration:

- Textile recycling can divert up to 4–5 $Mt \cdot yr^{-1}$ globally, addressing fast-fashion waste streams (Samardžioska et al., 2023).
- Paper recycling into insulation reduces pressure on paper mills and landfills, aligning with municipal waste recovery targets (Liuzzi et al., 2023).
- Rubber tyre valorisation prevents microplastic leaching from stockpiled tyres, offering safer disposal routes (Thai et al., 2020).
- Fly ash utilisation addresses the challenge of disposing >700 $Mt \cdot yr^{-1}$ of ash globally (Omerašević et al., 2024).

This highlights the role of waste-derived insulators as dual-purpose solutions, tackling both climate change and waste management.

End-of-Life Scenarios

End-of-life treatment strongly influences LCA outcomes.

- Single-material wastes (paper, textiles) are potentially recyclable or biodegradable, though contamination from binders or flame retardants can limit recovery.
- Hybrid composites present recycling challenges due to multi-material bonding (Aldaou et al., 2025).
- Plastics are recyclable but risk downcycling or incineration with emissions of toxic compounds (Zhang, 2024).

- Geopolymers and ceramics are inert and durable but non-recyclable, generally ending in landfill or reuse as aggregate.

Designing insulation materials for easy disassembly and mono-materiality will be key to achieving circularity.

Trade-offs and Challenges

Despite clear benefits, LCAs identify trade-offs:

- Additive use (fire retardants, hydrophobics) increases embodied energy and may introduce toxicity (Raj et al., 2020).
- Long-distance transport of bulky wastes can erode carbon savings (Rubino & Liuzzi, 2024).
- High-tech processes such as aerogel synthesis remain energy-intensive, requiring renewable energy integration to be sustainable (Chen et al., 2023).

Furthermore, standardisation is lacking: most LCAs rely on lab-scale prototypes, limiting transferability to real markets. Harmonised methodologies under EN 15804 and ISO 14040/44 are needed for comparability.

Synthesis

Table 3. Embodied carbon footprint of waste-derived and conventional insulation materials.

Material	**Embodied Carbon (kg CO_2-eq·kg^{-1})**	**Reference**
EPS foam	4.5	Alam et al. (2020)
Mineral wool	2.5	Papadopoulos (2019)
PET foams	3.0	Kucukvar et al. (2021)
Recycled textiles	0.8	Asdrubali et al. (2020)
Paper insulation	1.0	Korjenic et al. (2019)
Fly ash geopolymers	1.2	Zhang et al. (2023)

Overall, LCAs indicate that waste-derived insulators can deliver 30–80% reductions in embodied carbon compared to conventional insulation, while simultaneously reducing waste management burdens. However, end-of-life strategies and supply chain logistics remain bottlenecks. To maximise sustainability, future designs should prioritise mono-material approaches, renewable-energy processing, and integration with local waste management infrastructures.

IMPLEMENTATION CHALLENGES AND RESEARCH NEEDS

Although waste-derived thermal insulators demonstrate strong technical and environmental potential, their adoption in mainstream construction remains limited. Barriers span across regulatory, technical, economic, and socio-cultural dimensions. Addressing these systematically is essential for transitioning from laboratory-scale prototypes to commercially viable materials.

Regulatory and Standardisation Barriers

Building insulation materials must comply with stringent thermal, fire safety, moisture resistance, and durability standards under frameworks such as EN 13162–13171 (Europe) and ASTM C518/C177 (USA).

- Waste-derived materials often lack standardised testing protocols, leading to inconsistent reporting of thermal conductivity, density, or hygrothermal behaviour (Cieślak, 2025).
- Fire performance is a major hurdle: while mineral waste-based insulators excel, most fibrous and polymeric insulators require flame retardants, which may conflict with toxicological and environmental regulations (Raj et al., 2020).

- Certification pathways remain underdeveloped; many promising waste-based materials are restricted to niche pilot projects rather than being codified into building codes.

Research need: Development of standardised characterisation methods and performance benchmarks tailored to heterogeneous waste streams.

Scalability and Supply Chain Logistics

Scaling waste-derived insulation requires consistent feedstock quality and regional supply chain integration.

- Textile and paper waste streams are highly heterogeneous, with fibre blends and contaminants influencing performance (Nguyen et al., 2021).
- Collection and sorting systems are underdeveloped in many regions, limiting raw material availability (Samardžioska et al., 2023).
- Transporting bulky, low-density wastes over long distances increases the carbon footprint, offsetting environmental benefits (Rubino & Liuzzi, 2024).

Research need: Exploration of decentralised, small-scale production units near waste sources, supported by digital tracking and sorting technologies.

Performance Variability and Durability

Waste-derived insulators exhibit greater variability in performance compared to conventional materials.

- Moisture uptake in lignocellulosic and textile wastes reduces thermal efficiency over time.
- Biological degradation (fungi, insects) remains a concern for untreated organic wastes (Gaspar, 2020).
- Mechanical stability under cyclic loading and environmental exposure is often under-researched (Dama et al., 2025).

Research need: Long-term accelerated aging studies simulating real-world service conditions to quantify durability and establish maintenance requirements.

Economic and Market Acceptance

While waste-derived insulators are theoretically low-cost, several hidden costs hinder competitiveness:

- Processing steps (e.g., aerogel synthesis, geopolymer foaming) may be capital- and energy-intensive.
- Additive incorporation (binders, flame retardants, hydrophobic agents) increases costs and complexity.
- Market perception associates “waste materials” with low quality or safety risks, limiting consumer acceptance (Lisowski, 2025).

Research need: Comprehensive techno-economic analyses (TEA) and market studies to identify cost-effective scale-up strategies and address socio-cultural barriers through awareness campaigns.

Policy and Incentive Structures

Policies that promote circular construction practices can accelerate adoption:

- Public procurement strategies could mandate a percentage of recycled-content insulation materials in government buildings.
- Carbon pricing and landfill taxes would improve the competitiveness of waste-derived products (Platt et al., 2023).
- Incentives for eco-innovation and certification would foster industrial uptake.

Research need: Interdisciplinary work combining materials science, policy analysis, and industrial ecology to co-design supportive frameworks.

Future Research Directions

From the synthesis of recent literature, five priority directions emerge:

1. Standardisation: Development of harmonised test protocols for waste-derived insulators across thermal, fire, and hygrothermal domains.
2. Durability enhancement: Integration of bio-based coatings and nano-additives for moisture/fire resistance without compromising recyclability.
3. Digital waste valorisation: Use of AI-driven sorting and blockchain-based traceability to ensure consistent feedstock quality.
4. System-level assessment: Multi-scale LCAs and TEAs capturing regional variations in waste streams, processing energy, and building climates.
5. Policy integration: Collaboration between academia, industry, and regulators to accelerate certification and uptake in green building standards (LEED, BREEAM, DGNB).

Synthesis

Implementation challenges are significant but not insurmountable. By addressing performance variability, standardisation gaps, and economic feasibility, and embedding solutions within policy and circular economy frameworks, waste-derived insulators could transition from experimental innovations to mainstream sustainable building solutions.

CONCLUSION

This paper highlights the significant potential of upcycled waste materials as sustainable thermal insulators for the built environment. With reported thermal conductivities in the range of 0.032–0.08 $W \cdot m^{-1} \cdot K^{-1}$, waste-derived products such as textile mats, paper boards, plastic foams, rubber aerogels, agricultural composites, and geopolymer foams demonstrate performance comparable to or exceeding that of conventional mineral wool and petrochemical-based foams. Beyond technical feasibility, their integration contributes directly to circular economy objectives, offering dual benefits of waste diversion and carbon footprint reduction. Life cycle studies indicate up to 80% lower embodied emissions compared to traditional insulation, reinforcing their role as climate-resilient materials for sustainable construction.

Despite these advances, critical barriers remain. Feedstock variability, long-term durability, and regulatory certification challenges must be addressed to ensure consistent quality and safety. Advanced processing routes such as aerogel fabrication and geopolymerisation, while enabling superior performance, require optimisation to reduce costs and improve scalability. Furthermore, issues of fire resistance, moisture sensitivity, and microbial degradation necessitate material innovations, including hybrid composites and the use of bio-based additives. Market adoption also depends heavily on policy support, harmonised testing standards, and broader awareness among architects, engineers, and contractors.

Looking ahead, research should prioritise the integration of circular design principles at multiple scales—from material formulation and modular building systems to whole-life performance optimisation. The combination of waste valorisation, decentralised manufacturing, and industrial symbiosis holds promise for embedding these materials into mainstream construction supply chains. With coordinated efforts across academia, industry, and policy, upcycled insulation can move beyond niche applications to become a cornerstone of low-carbon, resource-efficient building practices. In doing so, these materials can play a transformative role in closing resource loops and advancing the circular solutions urgently needed for the future built environment.

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